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James L. Baker
Iowa State University

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James L. Baker
Professor
Department of Agricultural and Biosystems Engineering
Iowa State University

Introduction

Recent newspaper headlines in the Des Moines Register (e.g., October 19, 1994: "Water is laced with pesticides report finds - 14 million affected" and July 14, 1995: "River boosted drinking water nitrate levels - farm fertilizer suspected") illustrate some of the water quality concerns that exist for the off-site movement of pesticides and nutrients from treated fields to water resources. The major water quality concerns from pesticides relate to the possible impact on human health when found in surface and groundwater, and on the health of the aquatic ecosystem when found in surface waters. The major water quality concerns from nutrients, namely nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), and orthophosphate-phosphorus (PO_4-P), relate to the 10 mg/L (or ppm) drinking water standard for NO_3-N for prevention of "blue baby" or methemoglobinemia in infants, the level of concern of about 2 mg/L for NH_4-N to prevent fish toxicity from free ammonia (NH_3), and the levels of concerns in rivers of 0.050 mg/L and lakes of 0.025 mg/L for PO_4-P to prevent the acceleration of eutrophication.

In the recent past there has been considerable effort spent to understand and reduce the transport of agricultural chemicals to surface and groundwater resources. At this point it is known that three sets of factors are important in the fate and transport of pesticides and nutrients applied to the soil: 1) chemical factors, 2) hydrologic factors, and 3) management factors. The two most important chemical factors are persistence and soil adsorption. The longer a chemical exists in a field (of course it must exist for a while; if it is a pesticide, to control the target pest, and if it is a nutrient, to be taken up by the growing crop), the greater the chance of off-site loss. Soil adsorption, where an applied chemical sets up an equilibrium between being in solution in the soil water and being attached or adsorbed to soil, affects whether the method of off-site transport is sediment (for strongly adsorbed chemicals), surface runoff water (for moderately adsorbed chemicals), or leaching water (for weakly to non-adsorbed chemicals). Skipping over hydrologic factors, the main subject of this paper, to management factors, in-field practices such as the rate, method, and timing of chemical application; cropping; and tillage affect chemical concentrations and/or the volume of carrier (sediment, surface runoff water, or leaching water) that determines chemical loss. Off-site practices such as vegetated filter strips and constructed/restored wetlands can reduce concentrations and/or carriers, and therefore losses, between the field border and the water resource of concern.

The two primary hydrologic factors that affect the transport of agricultural chemicals are the rate of infiltration (relative to rainfall intensity or rate) and the route of infiltration (whether the infiltrating water moves through the whole soil matrix, or whether it finds "macropores" or preferential flow paths through which to move deeper, quicker "by-passing" much of the soil).

The purpose of this paper is to examine the theory and information that exists on these two factors in order to consider what options are available to manage infiltration to avoid water quality problems.

Current Understanding

Infiltration (in the vertical direction) refers to the entry of water into the soil profile from the surface. Two forces drive water to infiltrate into the soil, one is gravity, and the other is the attraction or "suction" of water by dry soil. Since water infiltration causes the soil to become wetter, the wetting front advances down into the soil with time. During the early stages of infiltration (at the beginning of a rainfall event), the suction forces predominate over the force of gravity and the infiltration rate is at its highest. But as time goes on, the infiltration rate decreases as the wetting front moves down into the soil away from the surface and the suction forces decrease. When the rainfall rate is less than the initial infiltration rate of the soil but greater than the final gravity-dominated rate, a point will eventually be reached where the water cannot be taken up by the soil profile as fast as it is being added. At this time, the surface soil becomes saturated, and ponding (and runoff from sloping soils) begins.

This is illustrated in Figure 1 for a rainfall simulation experiment where the rainfall rate was being held constant at 64 mm/h (2.5"/h) on a fallow plot without residue cover. As shown, 11 min into the rain the infiltration rate no longer exceeded the rainfall rate, and ponding and runoff occurred. Furthermore, the runoff rate, equal to the difference between the rainfall and infiltration rates, increased as the infiltration rate decreased with time. For this 2-h storm, 64 (one-half) of the 128 mm of rainfall applied ran off. Several infiltration equations or models have been derived to predict infiltration as a function of time. The one used in Figure 1 to fit the experimental data was the Philip equation:

$$i=1/2\ St^{-1/2}+A \qquad \text{(Eq. 1)}$$

where i is the infiltration rate (in mm/h or in/h), S is a constant related to the initial conditions of soil moisture content and the ability of water to move into the soil, and A is a longer-term constant.

Figure 2 illustrates why the rate and route of infiltration is important in determining chemical losses with surface and subsurface agricultural drainage. For transfer of chemicals from the soil into surface runoff, it is believed that there is a thin "mixing zone" at the soil surface from which chemicals are released. During a rainfall event the amount of chemical remaining in this mixing zone decreases with movement with water either over or down through this zone (with the rate of decrease greater for less strongly adsorbed chemicals). Obviously the higher the rate of infiltration, the longer it is before runoff begins and the lower the chemical concentration in runoff water (because infiltrating water has moved more of the chemical out of the zone of avilability). On the other hand, the route of infiltation, especially relative to preferential flows plaths or macropores as shown in Figure 2, can affect chemical leaching. If the chemical of concern is within soil aggregates, flow through macropores can by-pass it and leaching will be reduced. However, if the chemical is on the soil surface and dissolves in infiltrating water that is moving through macropores, leaching will be greater, quicker, and deeper than otherwise expected.

In addition to antecedent soil moisture contents, other important factors that affect the rate of infiltration (i.e. S and A in Eq. 1) are soil compaction, soil structure, and surface residue cover. Besides affecting infiltration rate, surface residue cover (and soil "roughness") creates ponding conditions which extend the time for infiltration to occur (and therefore the amount of infiltration). All these factors, including antecedent moisture content, can be affected to some degree by management practices such as drainage, controlled traffic, cropping, residue management, and tillage. The following section gives examples of studies showing the effects on infiltration and surface runoff of these practices with their measured or expected effects on water quality.

Experimental Studies

Subsurface drainage speeds the removal of excess soil moisture (that above field capacity) that may occur in the soil profile between rain storms and thus generally reduces the antecedent soil moisture before the next storm. This should reduce surface runoff and the transport of pollutants. There are limited data to verify this conclustion although Bengston et al. (1988) measured surface runoff as affected by subsurface drainage from a nearly level alluvial soil in the lower Mississippi Valley. The Commerce clay loam soil had been precision graded to 0.1% slope several years before the study. Four plots were established and monitored for flow and sediment loss; two with surface drainage only and two with surface plus subsurface drainage (drain tubes at 1 m depth at either a 10- or 20-m spacing). Over a six-year perod, surface runoff was decreased an average of 34% for the plots with subsurface drainage versus those without, although total drainage increased 35% when subsurface drainage was added to surface runoff. Over the same period, the annual soil loss was decreased an average of 30% for the plots with subsurface draingae (3482 kg/ha/yr) versus those without (4986 kg/ha/yr). Of the soil loss for the plots with subsurface drainage, 90% was with surface runoff and 10% was with subsurface drainage. Average sediment concentrations were 125 mg/L in subsurface drainage and 1244 and 1178 mg/L, respectively, for surface runoff with and without subsurface drainage. As discussed earlier, increased inflitration early in a storm delays the beginning of runoff and reduces pesticide concentrations in the surface soil "mixing zone" and thus in runoff water, particularly for the first storm runoff event after pesticide application when the greatest losses generally occur. Therefore, to a large degree, the effect of subsurface drainage on pesticide losses, as discussed for sediment loss, is then dependent on how use of subsurface drainage affects the hydrology of a field.

Additonal studies done in the lower Mississippi Valley (Southwick et al., 1990a and b; Bengtson et al., 1990) illustrates these effects for two herbicides. Atrazine (1.63 kg/ha) and metolachlor (2.16 kg/ha) were applied in April, 1987, to nine plots with 0.1% slope. Five of the plots had surface drainage plus subsurface drainage (parallel drain tubes 1 m deep at 10-, 20-, or 30-m spacing; four plots had only surface drainage. The quantity and quality of surface runoff and subsurface drainage were monitored for the 1987 growing season The hydrologic effect of subsurface drainage was to reduce surface runoff 37% for events in the first month after herbicide application and 38% for the growing season. Herbicide concentrations peaked in the first runoff event 123 days after application; however, the increased infiltration with subsurface drainage resulted in significantly lower atrazine (39% reduction from 275 to 167 μg/L) and metolachlor (37% reduction from 412 to 258 μg/L) concentrations in surface runoff. Lower concentrations combined with reduced runoff resulted in even greater decreases in herbicide losses in surface runoff early in the year; in May, atrazine and metolachlor losses were decreased 57 and 58%, respectively, by the existence of subsurface drainage. Corresponding values for the growing season were 56 and 56%. Herbicide concentrations also peaked in subsurface drainage at the time of the first rainfall runoff event after application at 3.5 and 29.3 μg/L for atrazine and metolachlor, respectively, but these concentrations were 9 to 79 times lower than those in surface runoff. Therefore, the overall impact of subsurface drainage was to reduce percentage losses and average concentrations in total drainage by at least half.

Compaction due to loading from implement traffic increases the bulk density and reduces porosity and the rate of infiltration in the compacted area. In a rainfall simulation study of herbicide transport (Baker and Laflen 1979), runoff, erosion, and propachlor (Ramrod), atrazine (AAtrex), and alachlor (Lasso) losses were measured for disked plots with and without tractor tracks. As shown in Table 1 for a 35 mm (1.4") rain, compaction caused 31% more runoff, 120% more sediment, and an average of 340% more herbicide loss. For the longer larger 122 mm (4.8") rain, corresponding values were 8, 42, and 270%. The reason that increases in herbicide losses were so much higher than increases in runoff and erosion is that the compaction from the wheel tracks had the greatest effect early in the storm, with more runoff and sooner, at a time when herbicide concentrations in runoff were highest. For the 35 mm rain (applied shortly after herbicide application), which is much more likely to occur than the 122 mm rain, 2 to 3% of each herbicide applied was lost for the untracked plots; overall over 4/5 of all herbicide losses occurred in solution in the runoff water (i.e. less than 1/5 was lost with sediment).

Cropping, particularly where close-grown crops are included, can increase infiltration and reduce runoff volumes and losses of chemicals. In a natural rainfall study of atrazine transport from a hillside (Hall et al., 1983), runoff, erosion, and atrazine losses with water and soil were measured for 22 m long plots, one set planted all to corn and a second set, designated stripped plots, with the bottom 6 m planted to oats. As shown in Table 2, for the 2.2 kg/ha (2.0 lb/ac) atrazine application rate without the oats strip there was 560% more runoff, over 7000% more erosion, and 1060% more atrazine loss than with the oats strip. Corresponding values for the 4.5 kg/ha (4.0 lb/ac) rate were 74, 197, and 175%. Most of the differences between the two rates, particularly for runoff and erosion, are likely due to plot variability; however, for both rates the oats acted as an efficient buffer strip increasing infiltration and reducing overland atrazine transport.

Crop residue on the soil surface, by protecting the soil against rainfall energy and surface sealing, maintains a higher infiltration rate, and the barrier to flow or damming effect of surface residue extends the time for infiltration to occur. In a rainfall simulation study of the effect of herbicide transport (Baker et al., 1982), measurements of runoff; erosion; and propachlor, atrazine, and alachlor losses were made for plots covered with 0, 375, 750, and 1500 kg/ha (0, 335, 670, and

1340 lb/ac) corn residue. As shown in Table 3, lack of corn reside caused runoff to occur soon and produced 21, 47, and 250% more runoff compared to 375, 750, and 1500 kg/ha residue covers (residue was distributed by hand, and it was roughly estimated that the 1500 kg/ha rate gave a 60% surface coverage). Corresponding values for erosion were 93, 395, and 1325%, and for average herbicide losses were 92, 173, and 630%. As shown from the time to beginning of runoff data, the biggest influence of corn residue on infiltration rates was early in the rainfall event when herbicide concentrations were the highest, and thus herbicide losses (taking place mostly with runoff water) were decreased more than runoff volumes. For the 1500 kg/ha rate, 32 mm (1.25") of rain infiltrated before runoff even began.

Mechanical tillage, or lack of it, affects both surface conditions, including roughness, pondage areas, and porosity, as well as surface residue cover. In a rainfall simulation study of the effects of surface conditions exclusive of residue (Cogo et al., 1984), measurements were made of time to beginning of runoff, initial infiltration, and runoff on plots from which crop residue was removed. As shown in Table 4, the increased roughness and porosity created by tillage increased initial infiltration and decreased total runoff relative to no-till. As also is shown, the more recent tillage (spring sweep) significantly increased initial infiltration over "aged" (fall) tillage surfaces. However, as evidenced by only a small difference in total runoff for the three tilled areas for the 2-h storm, the effect was apparently not long-lived.

The effect of tillage-induced increased infiltration, but sometimes of short duration, is evident in other sutdies. For example, in a five-year study of runoff from adjacent row-cropped watersheds (Hamlett et al., 1984; twenty-one less-severe events), with one exception, if an event occured after all primary and secondary tillage had been performed, but before any cultivaiton, the watershed that had been moldboard- or chisel-plowed, as opposed to the watershed that was only disked, had the least if any runoff. If cultivation had been performed on either or both of the watersheds, the more recently cultivated watershed had the least runoff. However, for four severe rainfall events, ranging from 42 to 74 mm, differences in runoff volumes from the two watersheds were evened out and runoff volumes were nearly identical.

In another study (Baker and Laflen, 1983a), rainfall simulations were performed 6 and 18 days after fall tillage on chisel-plow, disk, and no-till plots that had been grown to soybeans. For the first simulation, 2.5, 10, and 15% of the 111 mm of rain ran off for the chisel plow, disk, and no-till treatments, respectively. For the second simulation, performed on the same plots, the corresponding values for 72 mm of rain were 13, 48, and 19%. The contrast between the disk and no-till treatments was particularly striking, with runoff from the disked plots increasing from only two-thirds that of the no-till plots for rain one, to almost three times that of the no-till plots for rain two. It is believed leveling and surface sealing from rainfall impact on the less protected soil in the disked plots was mainly responsible for the change.

The long-term (from storm event to storm event) changes in relative infiltration rates are important when considering chemicals that dissipate over the growing season. As several reviews indicate (Wauchope, 1978; Baker, 1980; and Baker and Laflen, 1983b) it is usually the first storm after chemical application that results in the greatest percentage of chemical lost with surface runoff. Therefore it is conceivable that a tillage system which annually has the most runoff may not have the largest chemical loss if, for that system, chemical application closely follows a tillage practice that temporarily increases the relative infiltration rate.

In reviewing several runoff studies under simulated and natural rainfall (Baker, 1987), some patterns of the gross effects of conservation tillage on runoff volumes begin to emerge. Data for the rainfall simulation studies indicate that conservation tillage usually reduces surface runoff volumes between 10 and 50% relative to moldboard plowing. Furthermore, with only one exception, the chisel plow system resulted in a greater reduction than no-till, and no-till treatments sometimes exhibited more runoff than conventional tillage. However, rainfall simulation studies usually are short-term studies, which may mean they are run on areas with recently established tillage systems. In addition, they are usually run with long duration, intense rainfalls (e.g., 63.5 mm/h for 2 h), which, as indicated earlier, can even out differences that would otherwise exist for smaller rains. Results of studies under natural rainfall, most of which involved no-till, give a slightly different picture than the rainfall simulation studies. The longer-term nature of these studies means that the tillage system had been established for a while, and under natural rainfall, rains of all descriptions can occur. As a result, no-till on the average (but again with a wide range) reduced runoff by over 50% with the limited data possibly showing the chisel plow system to be less efficient than no-till in reducing runoff.

Use of the word efficient in describing reduction of runoff may not be appropriate if the water that does not run off, but instead infiltrates with some in excess of soil storage, percolates through the soil leaching chemicals with it. This is where the volume and route of infiltrating water become important. It is logical that the more infiltration that takes place, the more water that will potentially drain from the root zone. Since, in most instances, it is neither feasible nor appropriate to increase runoff to avoid infiltration and leaching, the approach to reduced chemical leaching (primarily for NO_3-N) that has some potential is to take advantage of the route of infiltration. One such approach is to inject nitrogen into the ridge in a ridge-tillage system with the logic being that during intense rainstorms water will "shed" off from the ridges with more water infiltrating through the valleys than through the ridges such that the ridge acts somewhat as an "umbrella." In a rainfall simulation study on anion leaching (Hamlett et al., 1990), measurements of NO_3-N and bromide (Br, used as a tracer) movement with 24, 50, and 72 mm of rain were made for ridge-tillage and flat plots. Soil analyses for water, NO_3-N, and Br showed that placement of anions in the elevated portion of a ridge reduced their leaching compared to a similar application with flat tillage, even though total water movement through both systems was comparable. Vertical NO_3-N and Br movement was much greater than horizontal movement, and the depth of downward movement increased as the amount of simulated rainfall increased.

In a second approach, work has been done to determine if it is feasible to manipulate the soil during N application to force the major portion of infiltrating water to move in zones remote from the zone of N fertilization. In separate large column studies (Kiuchi et al., 1994; Baker et al., 1995), the leaching of NO_3-N and other anion tracers has been reduced by compacting the soil or placing barriers above the zone of chemical application. In another study (Ressler et al., 1995), a field-scale machine has been built and is being tested that places liquid N fertilizer in a line, cutting and smearing any macropores within a few cm, compacting the soil above the line, and finally doming a small amount of soil at the surface over the line. Results from preliminary leaching measurements are encouraging.

Options Available to Manage Infiltration

In summary, practices to maintain or increase infiltration volumes to reduce surface runoff losses of agricultural chemicals can be either in-field or off-site, and they achieve this by increasing the rate of infiltration and/or extending the time for infiltration to occur. In-field practices can be categorized as: 1) avoiding soil compaction, 2) improving soil structure, 3) maintaining crop residue, and 4) creating roughness or pondage areas. With respect to compaction, controlling traffic to reduce the percentage of area compacted; avoiding heavy loads and/or working or trafficking on wet soils to reduce compaction from loads on the soil surface; and not applying chemicals to the surface of compacted soils should all reduce surface runoff volumes and/or chemical concentrations, and therefore losses, in that runoff. Improving soil structure is both hard to do and hard to quantify. Generally, increasing the organic matter content (possibly through use of manure or producing and leaving as much crop residue as possible) and growing grass or other close-grown crops in rotation, result in improved structure and increased infiltration rates. In some areas, the use of conservation tillage, and particularly no-till, is believed to result in improved soil structure, including increased numbers of undisturbed macropores at the soil surface that can increase infiltration rates. By maintaining crop residue on the soil surface, the sealing effects of rainfall energy can be much reduced and also the pondage areas created by surface crop residue can both help maintain or increase the infiltration rate as well as extend the time for infiltration to occur (by the temporary storage of water behind "residue dams"). Finally creating pondage areas, beyond those from crop residue, through tillage and by row orientation (on the contour) and row configuration (e.g., ridge-tillage) can further increase infiltration.

Off-site practices that increase infiltration and reduce surface runoff losses of agricultural chemical are primarily related to either structures or use of vegetated areas, which actually may be within a field boundary, but yet between the edge of cropland and a surface water resource. Structures in the way of terraces (level to tile-outlet) or storage or retention ponds create water storage areas to extend the time for infiltration to occur. Vegetated areas, in the way of grassed waterways within a field, or buffer strips beyond the field boundary (and even strip-intercropping, where one of the crops is a close-grown crop) generally will have infiltration rates higher than row-crop land and reduce overland water flow. It is obvious, but should be emphasized, that all of these in-field and off-site practices to increase infiltration also reduce erosion and/or sediment transport, which has significant additional soil resource and water quality benefits.

Practices to reduce leaching of agricultural chemicals, primarily NO_3-N, from the bottom of the root zone must generally rely on controlling the route of infiltration and not on a decreased volume of infiltration. While practices could be devised to decrease infiltration, the likely negative economic (in terms of reduced crop production from limited water and aeration) and negative surface water quality effects make that an inappropriate solution to the leaching problem. Use of chemical placement relative to an existing surface configuration, such as nitrogen injection into the ridges in a ridge-tillage system, or relative to microscale soil management, where the soil might be compacted around and domed over the zone of nitrogen application, has the potential to reduce water movement, and therefore leaching, in the areas nitrogen is placed. However at this point, more research and demonstration work is needed to verify and optimize these approaches.

References

Baker, J.L. 1980. Agricultural areas as nonpoint sources of pollution. In: Environmental Impact of Nonpoint Source Pollution. Edited by M.R. Overcash and J.M. Davidson (p. 275-310). Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Baker, J.L. 1987. Hydrologic effects of conservation tillage and their importance relative to water quality. Chapter 6, In: Effects of Conservation Tillage on Groundwater Quality, T.J. Logan, J.M. Davidson, J.L. Baker, and M.R. Overcash (eds.), Lewis Publishers, Inc., Chelsea, MI.

Baker, J.L. and J.M. Laflen. 1979. Runoff losses of surface-applied herbicides as affected by wheel tracks and incorporation. J. Environ. Qual. 8:602-607.

Baker, J.L. and J.M. Laflen. 1983a. Runoff losses of nutrients and soil from ground fall-fertilized after soybean harvest. Trans. ASAE. 26:1122-1127.

Baker, J.L. and J.M. Laflen. 1983b. Water quality consequences of conservation tillage. J. Soil and Water Conservation 38: 186-193.

Baker, J.L. and J.M. Laflen, and M. M. Schreber. 1995. Potential use of localized compaction to reduce anion leaching (in review).

Baker, J.L. and J.M. Laflen, and R.D. Hartwig. 1982. Effects of corn residue and herbicide placement on herbicide runoff losses. Trans. ASAE 25:340-343.

Bengton, R.L., C.E. Carter, H.F. Morris and S.A. Bartkiewicz. 1988. The influence of subsurface drainage practices on nitrogen and phosphorus losses in a warm, humid climate. Trans. ASAE 31:729-733.

Bengton, R.L., L.M. Southwick, G.H. Willis and C.E. Carter. 1990. The influence of subsurface drainage practices on herbicide losses. Trans. ASAE 33: 425-418.

Cogo, N. P., W. C. Moldenhauer, and G. R. Foster. 1984. Soil loss reductions from conservation tillage practices. Soil Sci. Soc. Am. J. 48:368-373.

Hall, J.K., N.L. Hartwig, and L.D. Hoffman. 1983. Application mode and alternate cropping effects on atrazine losses from a hillside. J. Environ. Qual. 12:336-340.

Hamlett, J.M., J.L. Baker and R. Horton. 1990. Water and anion movement under ridge tillage: A field study. Trans. ASAE 33:1859-1866.

Hamlett, J.M., J.L. Baker , S. C. Kimes, and J. P. Johnson. 1984. Runoff and sediment transport within and from small agricultural watersheds. Trans. ASAE 27:1355-1363, 1396.

Kiuchi, M., R. Horton, and T. C. Kaspar. 1994. Leaching characteristics of repacked soil columns as influenced by subsurface flow barriers. Soil Sci. Soc. Am. J. 50: 1212-1218.

Ressler, D.E., J.L. Baker, T.C. Kaspar, R. Horton, and J. Green. 1995. Localized compaction and doming to increase N-use efficiency and reduce leaching. In: Proceedings, Clean Water - Clean Environment - 21st Century, Vol. III, pp. 215-218.

Southwick, L.M., G. H. Willis, R.L. Bengston and T.J. Lormand. 1990a. Effect of subsurface drainage on runoff losses of atrazine and metolachlor in southern Louisiana. Bull. Environ. Contam. Toxicol. 45:113-119.

Southwick, L.M., G. H. Wills, R.L. Bengston and T.J. Lormand. 1990b. Atrazine and metolachlor in subsurface drain water in Louisiana. J. Irri. Drain. Eng. 116:16-23.

Wauchope. R.D. 1978. The pesticide content of surface water draining from agricultural fields - a review. J. Environ. Qual. 7: 459-472.

Table 1. Plot runoff, erosion, and herbicide losses as affected by wheel tracks*

Treatment	Runoff mm	Erosion t/ha	Propachlor	Atrazine	Alachlor
			-----------------	g/ha	-----------------
35 mm rain:					
tracked	17	11	141	251	260
untracked	13	5	28	53	74
122 mm rain:					
tracked	96	47	253	446	492
untracked	89	33	60	110	171

*Herbicide application rates averaged 2.2 kg/ha (2.0 lb/ac); from Baker and Laflen (1979).

Table 2. Plot runoff, erosion, and atrazine losses as affected by cropping*

Treatment	Runoff mm	Erosion t/ha	Atrazine loss % (with water)	% (with soil)	% (total)
2.2 kg/ha					
corn	80	31.7	2.2	1.3	3.5
stripped	12	0.4	0.3	0.0	0.3
4.5 kg/ha					
corn	47	10.1	0.8	0.3	1.1
stripped	27	3.4	0.3	0.1	0.4

*Atrazine applied to corn areas at the two rates shown; from Hall et al. (1983).

Table 3. Plot runoff, erosion, and herbicide losses as affected by corn residue*

Residue	Runoff		Erosion	Propachlor	Atrazine	Alachlar
kg/ha	min**	mm	t/ha		%	
0	11	63	11.4	6.1	5.7	8.6
375	17	52	5.9	2.8	3.4	4.5
750	20	43	2.3	2.0	2.5	3.0
1500	30	18	0.8	0.8	1.0	1.0

* With 127 mm (5.0") rain in 2 h; from Baker et al. (1982).

** Time in minutes from start of rainfall to start of runoff.

Table 4. Initial infiltration and plot runoff as affected by surface conditions*

Tillage Practice	Time**	Initial Infiltration	Runoff
	min	mm	
fall moldboard plow	11	12	67
fall chisel-plow	13	14	64
spring sweep	37	39	59
no-till	3	3	102

* From Cogo et al. (1984).

** Time and infiltration to beginning of runoff; 128 mm (5.0") rain in 2 h; plots 4.5% slope on sil soil.

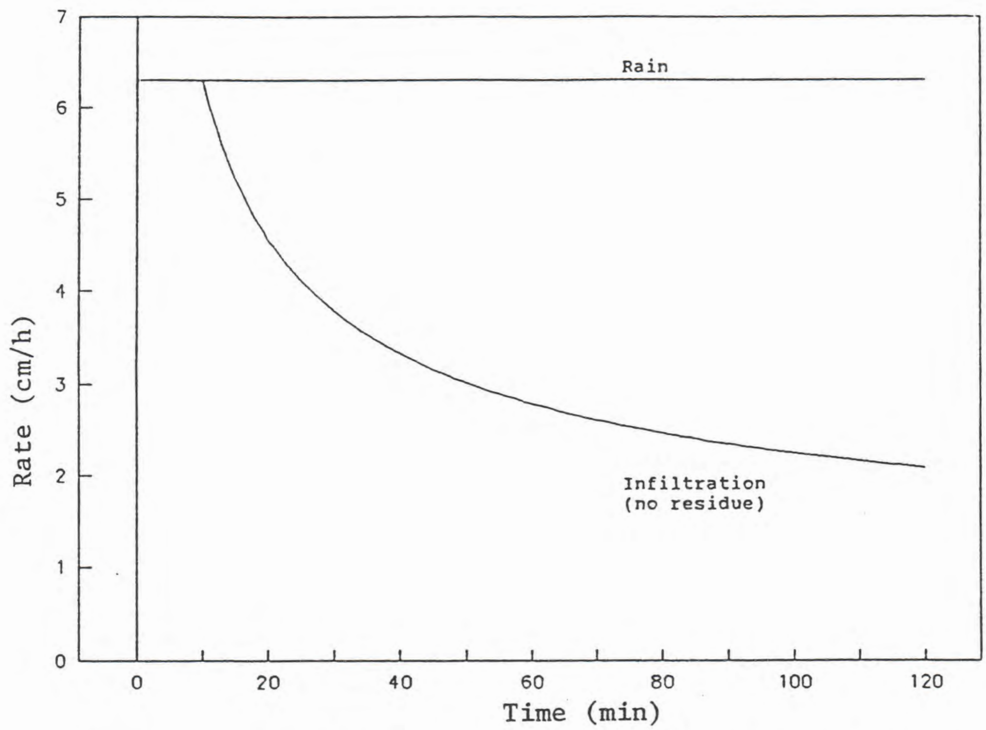

Figure 1. Rainfall and infiltration rates as a function of time

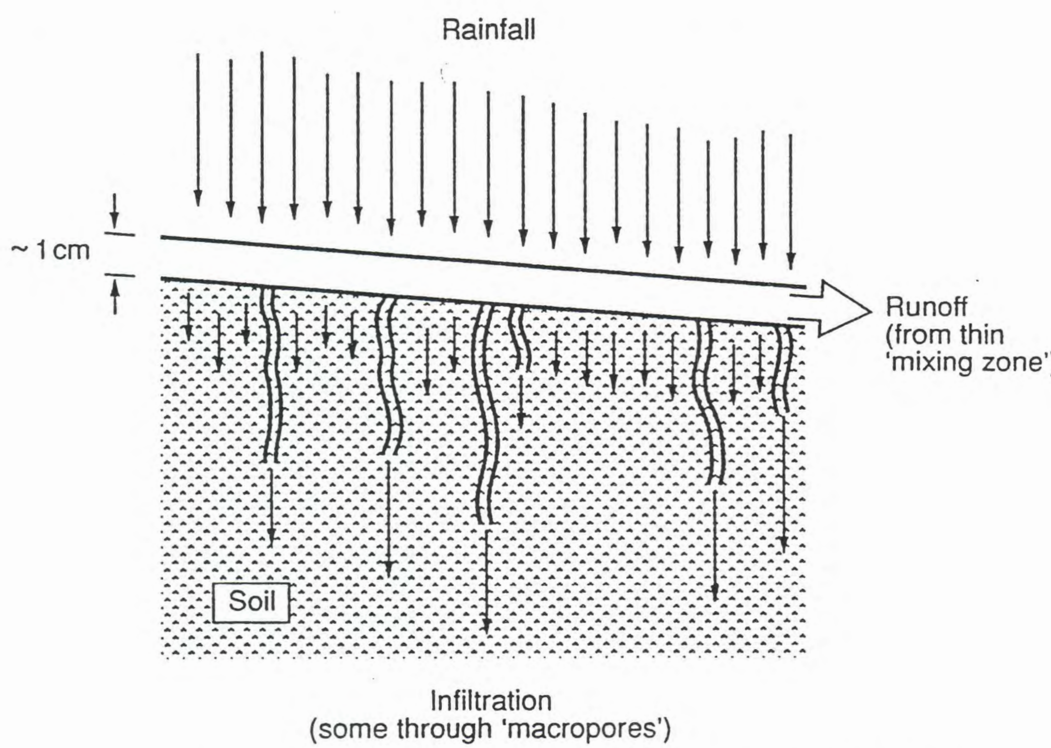

Figure 2. Schematic showing importance of mixing zone and macropores